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Ministry of Transportation
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Investigation of Lightweight Profiler Smoothness Measurements for Contract Acceptance and Network Monitoring

MERO-022

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Abstract

MTO currently bases smoothness acceptance of newly-constructed pavements on Profile Index (PI) and the height of individual bumps (or "scallops) measured by devices called California Profilographs. These devices operate at slow speeds of 4 to 5 km/hr and can only measure one wheelpath at a time.

This report summarizes a field study which compared California Profilographs with much newer and faster golf-cart-like devices called laser inertial (i.e. "lightweight") profilers, which can be used to measure both PI and International Roughness Index (IRI) for both wheelpaths simultaneously and at speeds of 15 to 20 km/hr. Since lightweight profilers take measurements much faster than California Profilographs, they are on the road less time and, as a result, are inherently safer.

During the fall of 2003, smoothness measurements were conducted on 10 asphaltic and 5 Portland cement concrete pavement sections at 8 different sites in Eastern Ontario using lightweight profilers, California Profilographs and MTO's Automated Road Analyzer (or ARAN) which is currently being used to monitor the long term performance of pavements in Ontario. A correlation between PI, as measured by the California Profilographs and IRI, as measured by the Lightweight Profilers, was used to develop IRI-based acceptance criteria which are "equivalent" to the current PI-based ones. Correlations of PI between both types of devices and correlations of IRI between lightweight profilers and MTO's ARAN were also determined, as well as the typical variances experienced by all three devices.

Based on the results of this study, it appears that lightweight profilers can be used to replace California Profilographs for either PI or IRI-based acceptance of new pavement construction. In addition, the very good correlation of IRI that was found between both the lightweight profilers and the ARAN suggests that IRI measurements on newly-constructed pavements can be used as a basis for the long term monitoring of those pavements (which is already being done in IRI).

However, before IRI can be used to replace PI on MTO contracts, an IRI-based measurement for the individual bumps must be created to replace the PI-based "scallops that are currently being specified. In addition, before the lightweight profilers evaluated in this study can be used for acceptance on MTO contracts, they would require some changes, especially in terms of data security (e.g. the inability to produce continuous profile traces and to prevent tampering of operator input factors recorded in header information). MTO is currently working towards resolving these challenges.

Key Words	Lightweight Profiler, Rate of Smoothness, Internal Roughness Index
Distribution	Unrestricted technical audience.

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Executive Summary

The most important qualities of a road are a smooth, uniformly-textured surface which provides riding comfort to motorists. New pavements with smooth riding surfaces result in lower vehicle maintenance costs and longer pavement life.

The smoothness of most new asphaltic and Portland cement concrete pavements constructed for the Ontario Ministry of Transportation (MTO) are currently being measured in units of Profile Index (PI) by a device called a California Profilograph. Since these devices are long (7.6 m) and unwieldy, they are operated at walking speeds (3-5 km/hr) and can only measure one wheelpath at a time, the hot mix industry has been asking for an alternative device that might be somewhat safer to operate.

This report summarizes the results of a field study which was conducted using much newer smoothness measuring devices called laser inertial (i.e. "lightweight") profilers. These "golfcarts" can be operated at speeds of 15 to 20 km/hr and used to measure both wheelpaths simultaneously in both PI and another smoothness statistic called International Roughness Index (IRI). Since lightweight profilers can take measurements much faster than California Profilographs, they are on the road less time and, as a result, are inherently safer to operate. The objectives of this study were to determine if:

I. These devices could be used to produce measurements comparable to those measured by the California Profilographs,
II. The emerging use of IRI could be used as an acceptance attribute for new construction to replace PI, and
III. If IRI measurements produced by these devices could be integrated into a network data base for long term monitoring.

During the fall of 2003, three lightweight profilers, three California Profilographs and MTO's Automated Road Analyzer (ARAN) measured 10 asphaltic and 5 Portland cement concrete pavement sections at 8 different sites in Eastern Ontario. A correlation between PI, as measured by the California Profilographs and IRI, as measured by the Lightweight Profilers, was used to develop IRI-based acceptance criteria "equivalent" to the PI-based ones. Correlations of PI between both types of devices and correlations of IRI between lightweight profilers and MTO's ARAN were also determined, as well as the typical variances experienced by the lightweight profilers and the ARAN.

Based on the results of this study, it appears that, in most cases, lightweight profilers can be used to suitably replace California Profilographs for either PI or IRI-based acceptance of new pavement construction. In addition, the very good correlations of IRI between the lightweight profilers and the ARAN suggests that IRI measurements taken for acceptance of new construction could be used as a basis for the long term monitoring of those same pavements.

However, before such devices can be used on MTO contracts, all of the lightweight profilers that were evaluated in this study would require some changes, especially in terms of data security (e.g. the inability to produce continuous profile traces and to prevent tampering of operator input factors recorded in header information). There are also some other issues, which need to be addressed, related to the operation of the types of sensors that are being used. MTO is working towards resolving these contract administration and operational concerns and a specification is being prepared for use in future contracts.

1. INTRODUCTION

The Ontario Ministry of Transportation (MTO) implemented a smoothness specification for hot mix paving in 1997. After having applied smoothness requirements for the past seven years, the riding comfort of Ontario highways has improved by some 25 percent.

For most new asphaltic and Portland cement concrete pavements, which are constructed in Province of Ontario, Rate of Smoothness [(RS) - one wheelpath] or Profile Index [(PI) - average RS for both wheelpaths], as measured by the California Profilograph, has been used for smoothness acceptance.

A California Profilograph consists of a 7.6 m long aluminum truss supported by bogey wheels with a centrally-located, pneumatic measuring wheel which is secured to a moveable arm that moves up and down as the device is pushed down the road. Since California Profilographs can only measure one wheelpath at a time and the measurements are taken at a relatively slow pace (at about 4 km per hour), the hot mix industry has been asking for an alternative device that is quicker and safer to operate.

At the network monitoring level, MTO has been using International Roughness Index (or IRI), as measured by the Automated Road Analyzer (ARAN). IRI is a roughness statistic that is calculated from the "true profile" of the road. The ARAN can measure pavement smoothness in both wheelpaths using laser sensors and devices called accelerometers (which eliminate any bouncing of the vehicle) as the device moves down the road at highway speed.

So far, the smoothness of pavements in Ontario has been measured using two different indices (both PI and IRI) during their lives. It was recommended that "cradle-to-grave" measurements should only be based on IRI.

2. PURPOSE AND PLAN OF INVESTIGATION

A project was undertaken to investigate if:

i) Laser inertial (i.e. lightweight) profilers could be used to produce measurements comparable to those measured by the California Profilographs,
ii) The emerging use of IRI could be used as an acceptance attribute for new construction to replace PI, and
iii) If IRI measurements produced by laser inertial profilers could be integrated into a network data base for long term monitoring.

With these objectives in mind, the study was divided into the following tasks:

1) A literature review was carried out to determine which type of IRI-based device, that is currently on the market, could most suitably replace the California Profilograph. Ideally the type of device chosen could measure IRI (and hopefully PI) in both wheelpaths simultaneously, at somewhat greater speed than a California Profilograph.
2) In the second part of the project, a field study was undertaken to compare the device chosen in the literature review to both California Profilographs and the MTO's ARAN.
3) In the final part of the project, the data generated from the field study was used to develop correlations between all three types of devices that were investigated, and to develop acceptance criteria based on IRI that could be used in a specification for new construction.

3. SELECTION OF MEASURING DEVICES

A literature search was carried out to investigate the various types of IRI-based road profilers that could be used to replace the California Profilograph {Karamihas and Gillespie [1], Sayers and Karamihas [2]}. There were several different criteria that MTO was looking for in a profiler including the ability to:

- Measure IRI (and preferably RS and PI as well, if MTO intends to phase-in the device);
- Take measurements at a faster rate than a California Profilograph (i.e. inherently the less time a device is on the road, the safer it is to operate).
- Take measurements in both wheelpaths simultaneously (i.e. inherently safer, as above); and
- Produce a hard copy "profile trace" for immediate identification of individual bumps or dips (i.e. "scallops" or "must-grinds") similar to those from a California Profilograph since:

    - There is currently no reliable IRI-based method to identify individual bumps or "scallops", yet they are found to have a greater affect on penalties than overall smoothness; and
    - It is found that a continuous profile trace with all of the appropriate input factors in the header that can be signed and dated is the best way to ensure the integrity of the data.

The two main types of devices that were found to meet the majority of the criteria mentioned above include:

1) Devices that operate at highway speed (like MTO's ARAN) and,
2) Laser Inertial (i.e. "Lightweight") profilers

a) High Speed Devices

In MTO's asphalt contracts, the Contractor's QC smoothness measurements are used for acceptance. Ontario's contractors want to be able to measure pavement sections immediately after paving and before they are subjected to traffic. Since newly-constructed sections are usually relatively short (i.e. several hundred metres to a kilometre), devices that operate at highway speed are probably impractical because they often require several hundred metres to get up to the required speed for measuring and then slow down after each section is measured. Also, at that time, none of the types reviewed were able to produce a "profile trace" which would be needed to identify individual "scallops".

b) Slow Speed Devices

The slower lightweight profilers (10 to 35 km/hr) were found to be the only class of devices that appeared to meet the criteria listed above.

A lightweight profiler consists of a golf cart or some other vehicle (Figure 1) equipped with lasers or infrared sensors which are used to take measurements of the road surface profiles from a fixed reference point. Like the high speed devices, these profilers are also equipped with accelerometers which are used to maintain a fixed vertical reference point by cancelling out any bouncing of the vehicle, as it's driven down the road. All of the lightweight profilers investigated can be equipped with two sensors so that both wheelpaths can be measured simultaneously. The data produced can be used to calculate IRI and PI and print out a PI-based profile trace which can be virtually identical to the one produced by a California Profilograph.

Although, the lightweight profilers appeared suitable, there were several concerns that needed to be investigated such as:

- How the device measures very smooth or very rough pavements, when compared with a California Profilograph (i.e. what IRI-based acceptance limits would be equivalent to the PI-based ones that are currently being used);
- How reproducible/repeatable the results are; and
- How weather and other environmental conditions affect the equipment and results.

A field investigation was carried out to try to investigate these concerns using a similar approach to the ones provided by Karamihas and Gillespie [1] and the FHWA [4].

Figure 1 - Example of a Lightweight Profiler

4. FIELD INVESTIGATION

The fieldwork consisted of selecting and measuring several different pavement sections using lightweight profilers, California Profilographs and the Ministry's ARAN. The procedures and sequence of operation are described as follows:

4.1 Selection of Pavement Sections

MTO has been participating in a fuel consumption study, which is being co-ordinated by the Federal Government. It was considered desirable to include the five sites involved in that study (i.e. Sites 1, 2, 4, 5 and 8 shown on Figure 2), in this new Lightweight Profiler Study.

With the co-operation of Regional staff, approximately 20 other candidate sites representing a wide range of surface smoothness were identified. By March 2003, the candidate sites were driven over and their individual ride qualities assessed. Surface deficiencies were also noted and most of the sections were photographed. After evaluating the smoothness of all of the proposed sites, three of the 20 other candidate sites were eventually selected to add to the five fuel study sites that were already established. These sites were selected to cover the widest possible range of surface smoothness.

Two pavement sections, from 1.2 to 2.1 km long, were chosen at seven of the eight sites and a single 3.0 km pavement section was chosen at the remaining one (Site 2), representing a total of 15 pavement sections (or 284 - 100 m sublots)- five of which were concrete (or 72 - 100 m sublots) with the rest being asphalt. All of the pavement sections are summarized in Table 1.

Immediately prior to beginning the smoothness measurements, marks were painted onto the

pavement surface and clearly-marked wooden stakes were driven into the shoulder at both ends of each of the 15 pavement sections and at 500 m intervals between them.

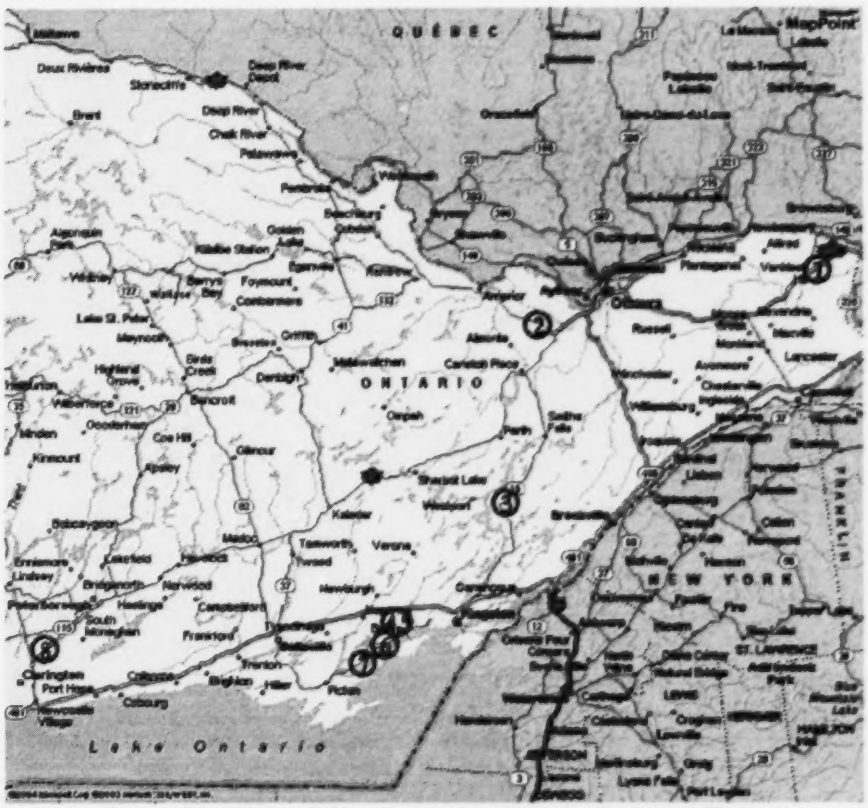
Figure 2 - Sites of Pavement Sections in Eastern Ontario

The surface of most of the pavement sections was generally in good to excellent condition with the following exceptions:

- Concrete sections 5A and 5B exhibited numerous moderate to severe cracking (several with spalled edges) throughout.
- Concrete section 8B exhibited slight to moderate cracking.
- Asphalt section 8A exhibited slight to moderate cracking at 5 to 12 m spacings.
- Asphalt sections 7A and 7B exhibited a few short patches.

The concrete pavement at sections 1A, 1B and 8B were transversely tined but no tining was found at sections 5A and 5B.

pavement surface and clearly-marked wooden stakes were driven into the shoulder at both ends of each of the 15 pavement sections and at 500 m intervals between them.



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The concrete pavement at sections 1A, 1B and 8B were transversely tined but no tining was found at sections 5A and 5B.

Table 1 - Summary of Pavement Sections

Site	Hwy	Location	Surface	Approximate Year(s) Last Paved	Length of Test Section
1A	417	km 22 to km 20.5 EB (East of Ottawa)	200mm of JPCP (concrete) and transversely tined	2002	1500
1B	417	km 19.5 to km 18 EB (East of Ottawa)	200mm of JPCP (concrete) and transversely tined	2002	1500
2	417	West of Ottawa	HL1	1999	3000
3A	15	North of CtyRd 42	HL1	2001	2100
3B	15	North of CtyRd 42	HL1	2001	2100
4A	L&A* CtyRd 2	W of Site4 at CtyRd 7	HL3	1997	2000
4B	L&A* CtyRd 2	W of Site4 at CtyRd 7	HL3	1997	2000
5A	L&A* CtyRd 4	between CtyRd 2 and Millhaven (southerly direction)	225mm of JPCP (concrete) no tining	1963	1200
5B	L&A* CtyRd 4	between CtyRd 2 and Hwy 401 (southerly direction)	225mm of JPCP (concrete) no tining	1963	1500
6A	33	East of Conway	HL4	1998	2000
6B	33	East of Conway	HL4	1998	2000
7A	33	Between Adolphustown and Conway	30/70 Recycled Hot Mix	2000/01	2000
7B	33	Between Adolphustown and Conway	30/70 Recycled Hot Mix	2000/01	2000
8A	115	at CtyRd 12 EB	HL1	1991/2	2000
8B	115	at CtyRd 12 WB	200mm JPCP w Dowels and transversely tined	1991/2	1500

*Lennox and Addington County Roads

4.2 Field Measurements and Collection of Data

Three lightweight profilers (all different manufacturers) and two California Profilographs (a McCracken and a Cox Bros.) were chosen to take the measurements through a competitive selection process. MTO provided a third California Profilograph (McCracken).

The measurements took place between October and November 2003. Since the profilographs were known to take measurements at a much slower pace than the lightweight profilers, the work was arranged so that the two types of devices would be measuring different sites on the same days. During the fieldwork, the temperature was generally below freezing (particularly at the beginning of the day). However, on a couple of days, the temperatures rose as high as 10 degrees celcius during the latter part of the day. The work was lengthened by three or four days because of rain.

Each lightweight profiler ran all of the pavement sections a minimum of three times (see Figure 2). Their operators were required to report RS (and PI) using both 0 and 5 mm blanking bands, International Roughness Index (IRI) as well as the locations and heights of all scallops from each run in both wheelpaths. The lightweight profilers were tested according to ASTM E950 [5] and the most recent versions of the AASHTO protocols [6, 7, 8].

Figure 3 - The Three Lightweight Profilers

The asphalt sections were tested by each profilograph running once on both wheelpaths (see Figure 4) using a zero (0) blanking band. However, the concrete sections were measured twice so that the data for those sections could be generated for both 0 and 5 mm blanking bands. The operators were required to report RS (and PI) as well as the locations and

heights of all scallops from each run in both wheelpaths. The profilographs were tested according to ASTM E 1274-88 [9] and MTO's latest smoothness specification for asphaltic concrete pavement [10].

Figure 4 - The Three California Profilographs

To avoid conflicts with the other two types of devices, MTO's Automated Road Analyzer or ARAN (see Figure 5) measured all 15 pavement sections somewhat later (i.e. between November and December 2003). As with the lightweight profilers, the ARAN operator measured each pavement section three times and reported IRI for both wheelpaths.

Figure 5 - MTO's Automated Road Analyzer (ARAN)

®Excel data templates were distributed to each operator of the three different devices. The operators were required to create separate data files for each pavement section. All of the accumulated data was sent to the MTO's Bituminous Section on either a floppy disk or CD as ®Excel and ERD files. The ®Excel templates were used to assemble a global ®Excel file which facilitated the data analysis and lead to the establishment of a separate ®Kaleidagraph plotting file

5. DATA ANALYSIS

The data obtained from the various measuring devices, was used to:

1) Develop a series of correlations between the lightweight profilers, the California profilographs and the ARAN;
2) Develop reliable IRI-based acceptance limits for new construction which are equivalent to the current PI-based ones;
3) Investigate the accuracy and reproducibility of the data; and
4) Determine how lightweight profilers locate and determine the heights of scallops when compared to California Profilographs.

In Ontario, the smoothness of new asphaltic concrete pavements constructed for MTO is currently being measured by California Profilographs in terms of Profile Index (PI). The current acceptance limits, which are based on a zero (0) blanking band to the nearest mm/km, are as follows:

Maximum Bonus:	< 150
Bonus:	151 to <230
Full Pay:	231 to 430
Price Reduction:	>430 to 550
Rejectable:	>550

5.1 Correlations between the average PI's and IRI's for Profilographs, Lightweight Profilers and MTO's ARAN

The data was used to determine a number of different correlations. The most important of these included:

- PI by Lightweight Profilers Versus PI by California Profilographs.
- IRI by Lightweight Profilers Versus PI by California Profilographs.
- IRI by Lightweight Profilers Versus IRI by MTO's ARAN.

The correlations which are presented here are based on the:

- Average PI's which have been determined from a single run of both wheelpaths by the three different profilographs (labelled P1, P2 and P3);
- Average PI's and IRI's which have been determined from the three runs of both wheelpaths by the three different lightweight profilers (labelled L1, L2 and L3); and
- Average IRI's which have been determined from three runs of both wheelpaths by MTO's ARAN.

It should be noted that the correlations involving PI, which are presented graphically, have been based solely on the zero blanking band. Although several correlations based on the 5 mm blanking band have also been developed (measurements of concrete pavements use a 5

mm blanking band), they will only be presented in tabular form (Table 2).

5.1.1. PI by Lightweight Profilers Versus PI by California Profilographs

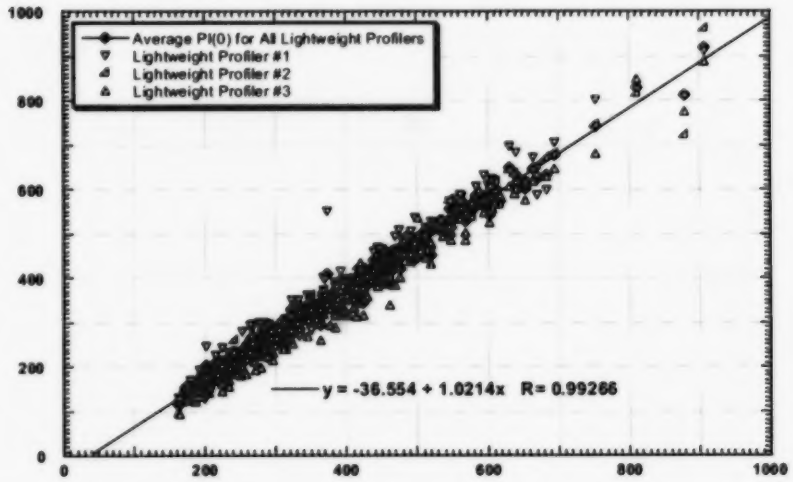
The objective of this comparison was to investigate how well a lightweight profiler is able to emulate the PI measurements taken by a California Profilograph, as used in MTO's current specifications.

Figure 6 shows a plot of the average PI's simulated by each of the three lightweight profilers in their 3 runs versus the combined average PI's measured by the three California Profilographs in their single runs for each 100 m sublot in the ten asphalt pavement sections that were tested. It is quite clear from this figure that there is an excellent linear relationship for PI(0) between the two types of devices (R = 0.993) which is given by the following equation:

$$PI_{Light} = -36.554 + 1.0214 \times PI_{Prof} \quad \text{(0 blanking band)} \qquad \text{(i)}$$

In addition, the correlation equations developed between each of the lightweight profilers shows that, there are also excellent linear relationships between the averages of each of the three devices when compared with the overall averages for the profilographs, with Lightweight Profiler #2 slightly outperforming the other two (R = 0.9909, Table 2).

Figure 7 shows a similar plot, but includes the results from the five concrete pavement sections. The results for this plot as well a similar equations for the concrete sections only ---- are summarized in Table 2, (i.e. R between 0.981 and 0.996), show that all of the correlation equations have excellent linear relationships when comparing PI measurements taken by lightweight profilers to those taken by the California Profilographs. Lightweight Profiler #2, again slightly outperformed the other two.



Average PI(0) by Lightweight Profilers in mm/km (average of both wheelpaths and 3 runs)

Average PI(0) by Profilographs in mm/km (Average of 2 wheelpaths and 1 run for all 3 profilographs)

Figure 6 - PI(0) by Lightweight Profilers Versus PI(0) by Profilographs (Asphalt Sections Only)

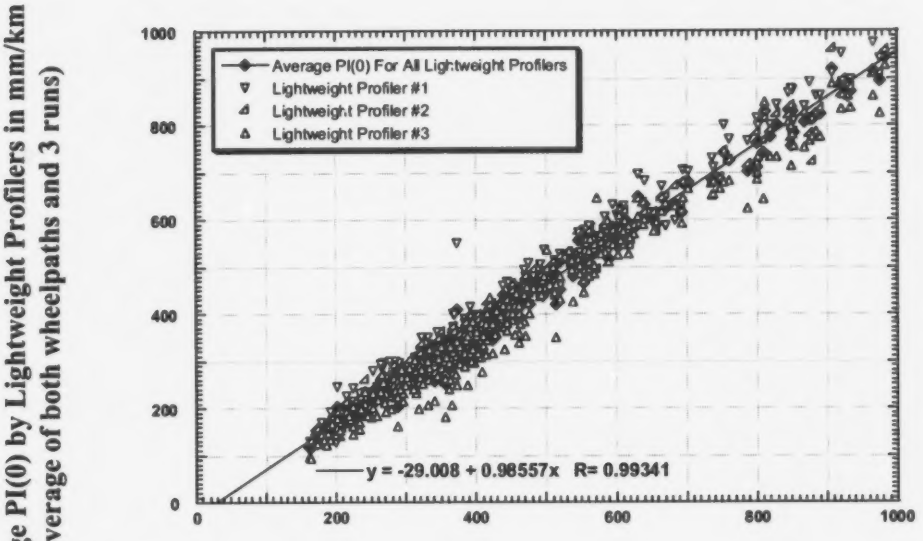


Figure 7 - PI(0) by Lightweight Profilers Versus PI(0) by Profilographs (All Pavement Sections)

Table 2. Summary of Correlation Equations Between Lightweight Profilers, California Profilographs and MTO's ARAN

Linear Correlations for 100 m sublots	Linear Constants and Correlation Coefficients											
	Lightweight Profiler #1			Lightweight Profiler #2			Lightweight Profiler #3			All Lightweight Profilers Combined		
	A	B	R	A	B	R	A	B	R	A	B	R
1) $PI_{Light} = A + B \times PI_{Prof}$												
a) 0 mm BB, Asphalt Sections Only	-27.157	1.025	.97998	-26.898	1.0090	0.9909	-50.326	1.0145	0.9863	-36.554	1.0214	0.99266
b) 0 mm BB, All Pavement Sections	-24.195	1.01	0.98969	-21.926	0.9810	0.9926	-39.156	0.9605	0.9843	-29.008	0.98557	0.99341
c) 0 mm BB, Concrete Sections Only	-47.033	1.0327	0.99424	-70.997	1.0310	0.9948	-115.18	1.0349	0.9875	-78.075	1.0333	0.99592
d) 5 mm BB, Concrete Sections Only	-9.7954	1.0166	0.98267	-3.623	0.9825	0.9922	-8.5255	0.8938	0.9809	-7.4956	0.96255	0.9921
2) $IRI_{Light} = A + B \times PI_{Prof}$												
a) 0 mm BB, Asphalt Sections Only	0.1844	0.00210	0.9261	0.2054	0.00210	0.9244	0.2096	0.00206	0.9183	0.1998	0.00209	0.9263
b) 0 mm BB, All Pavement Sections	0.1724	0.00213	0.9608	0.1955	0.00212	0.9578	0.2042	0.00205	0.9531	0.1907	0.00210	0.9599
c) 0 mm BB, Concrete Sections Only	0.1588	0.00216	0.9685	0.1462	0.00218	0.9646	0.0824	0.00219	0.9677	0.1291	0.00218	0.9696
d) 5 mm BB, Concrete Sections Only	1.0159	0.00306	0.9319	1.0092	0.00311	0.9334	0.9449	0.00313	0.9415	0.9899	0.00310	0.9382
3) $IRI_{Light} = A + B \times IRI_{ARAN}$												
a) Asphalt Sections Only	0.0123	0.9398	0.9880	0.0295	0.9436	0.9899	0.3495	0.9240	0.9808	0.0270	0.9358	0.9899
b) All Pavement Sections	0.0073	0.9511	0.9924	0.2647	0.9486	0.9939	0.0413	0.9117	0.9885	0.0250	0.9388	0.9944
c) Concrete Sections Only	0.0646	0.9277	0.9928	0.0432	0.9423	0.9940	-0.0123	0.9395	0.9914	0.0318	0.9227	0.9928

Note: A, B = Constants, BB=blanking band, IRI=International Roughness Index, IRI_{ARAN} = Average IRI determined by MTO's ARAN, IRI_{Light} = Average IRI determined by an individual lightweight profiler (or by all three combined), PI_{light}=Average Profile Index determined by an individual lightweight profiler (or by all three combined), PI_{Prof}=Average Profile Index determined by all three profilographs, R=Correlation Coefficient

5.1.2 IRI by Lightweight Profilers Versus PI by California Profilographs

One of the objectives of this study was to determine if IRI could be used to replace PI as an attribute for smoothness acceptance. Therefore, the relationship between the IRI's measured by the Lightweight Profilers and the PI's measured by the California Profilographs was investigated.

Figure 8 shows a plot of the average IRI's measured by the three lightweight profilers in their 3 runs versus the combined average PI's measured by the California Profilographs (using a zero blanking band) in their single runs for the 10 asphalt pavement sections. As

this figure shows, there is a good linear relationship between the measurements taken by both types of devices (R = 0.926), although there was somewhat greater variation when the PI's were greater than about 430 mm/km. Also, more variation was found here than when the PI's (i.e. subsection 4.1.1) were compared between the two devices. This greater variation is to be expected, since the wavelengths that are being measured by the two types of devices are really quite different. The correlation equation for the best-fit line representing the overall averages of the IRI's measured by the lightweight profilers versus the PI's measured by the profilographs is given by the following equation:

$$IRI_{Light} = 0.1998 + 0.002088 \times PI_{Prof} \quad \text{(0 blanking band)} \qquad \text{(ii)}$$

Good linear relationships (Figure 9) were also found when the five concrete pavement sections were added to the results (0.960) or when the concrete sections were tested alone using either 0 or 5 mm blanking bands (R = 0.938 to 0.970). Again slightly more variation was measured than in the comparable PI versus PI plots.

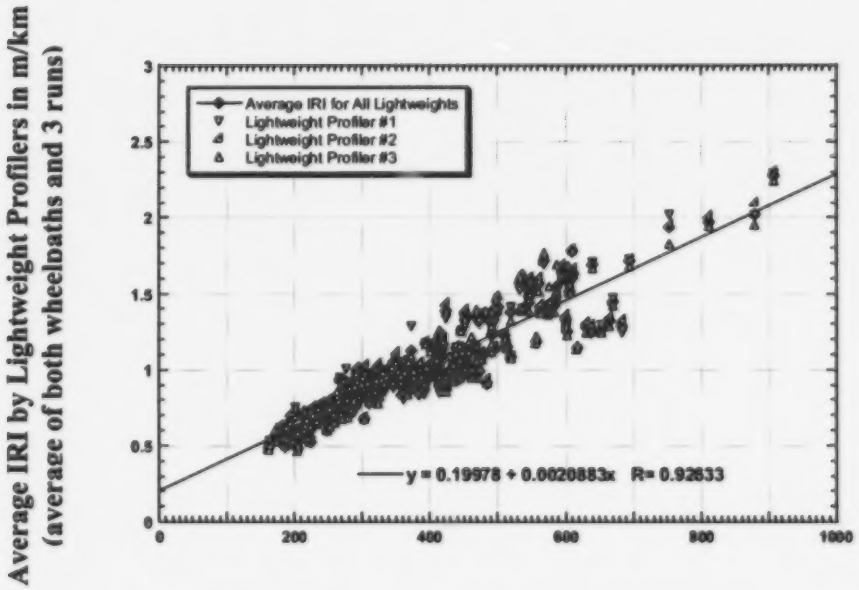


Figure 8 - IRI by Lightweight Profilers Versus PI(0) by Profilographs (Asphalt Sections Only)

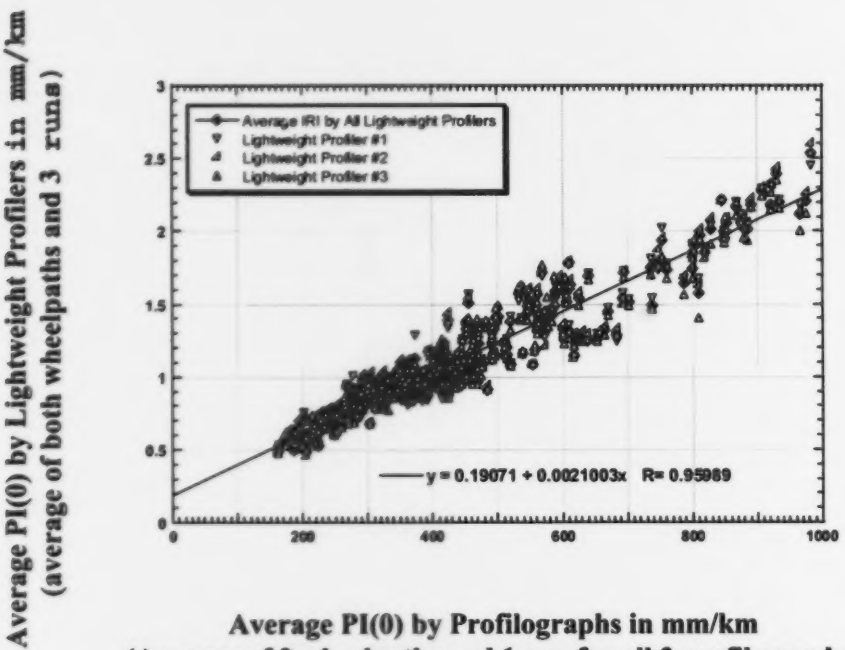


Figure 9 - IRI by Lightweight Profilers Versus PI(0) by Profilographs (All Pavement Sections)

5.1.3 IRI by Lightweight Profilers Versus IRI by ARAN

The last group of correlations were carried out to determine the feasibility of using IRI measurements taken by the lightweight profilers for new construction as a basis for future network level smoothness monitoring (i.e. "cradle-to-grave" measurements) of the same pavements. The relationship between the average IRI's measured by the three lightweight profilers in their three runs and the average IRI's measured by MTO's ARAN in its three runs (Figure 10) was determined. An excellent linear correlation was found between the two variables (R = 0.99), as given by the following equation:

$$IRI_{Light} = 0.02705 + 0.9358 \times IRI_{ARAN} \quad \text{(0 blanking band)} \qquad \text{(iii)}$$

Excellent linear correlations were also found when the 5 concrete sections were added to the results (see Figure 11) or when the concrete pavement sections were tested alone.

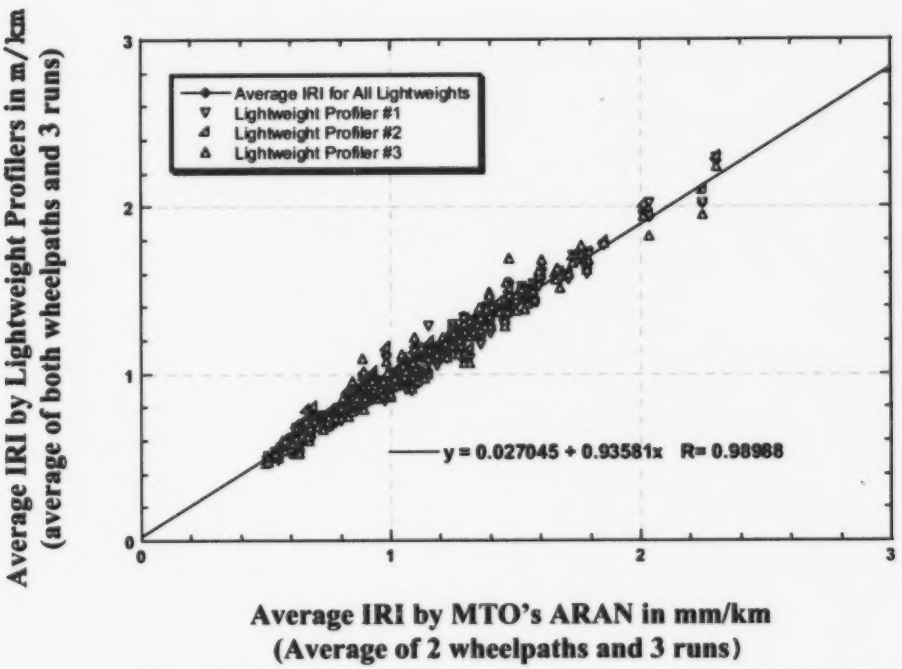

Average IRI by Lightweight Profilers in m/km
(average of both wheelpaths and 3 runs)
Average IRI for All Lightweights
Lightweight Profiler #1
Lightweight Profiler #2
Lightweight Profiler #3
y = 0.027045 + 0.93581x R= 0.98988
0
1
2
3
Average IRI by MTO's ARAN in mm/km
(Average of 2 wheelpaths and 3 runs)

Figure 10 - IRI by Lightweight Profilers Versus IRI by MTO's ARAN (Asphalt Sections Only)

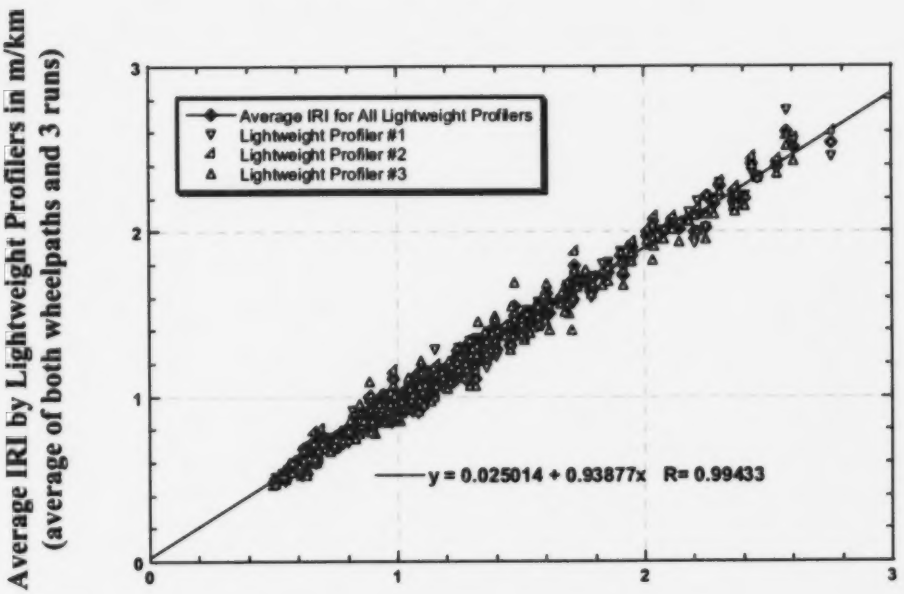

Average IRI by Lightweight Profilers in m/km
(average of both wheelpaths and 3 runs)
Average IRI for All Lightweight Profilers
Lightweight Profiler #1
Lightweight Profiler #2
Lightweight Profiler #3
y = 0.025014 + 0.93877x R= 0.99433
0
1
2
3
Average IRI by MTO's ARAN in m/km
(Average of 2 wheelpaths and 3 runs)

Figure 11 - IRI by Lightweight Profilers Versus IRI by MTO's ARAN (All Pavement Sections)

5.2 Correlation Simulations and Rate of Smoothness (RS)/IRI Variability for the Lightweight Profilers

In order to enable Lightweight Profilers to be used for acceptance in current contract specifications, simulations were needed to evaluate the variability of both the RS (or RI) and IRI measurements. Currently, MTO conducts RS(0) correlations between all of the profilographs that will be used on MTO contracts, prior to the beginning of each construction season. During those correlations, each profilograph is required to run a continuous 300 m section of a single wheelpath (i.e. 3 profile sections of 100 m each) three times. Using the data that is generated, the acceptability of each of the profilographs is determined on the basis of the following acceptance criteria:

1) Reproducability: The average RS(0) for the 300 m section of a single wheelpath run three times, must be within 4 percent of its overall mean established by all of the participating devices.

2) Repeatability: The average coefficient of variation (i.e. the ratio of standard

deviation to the mean) of RS(0), for all 3, 100 m sections within that 300 m, expressed as a percentage, must be less than or equal to 5 percent in accordance with the following equation.

$$\left[\frac{\sum_{i=1}^{3}\frac{s_i}{\overline{X}_i}}{3}\right]\times 100 \le 5\% \quad \text{.....(iv)}$$

Where: s_i and $\overline{X}_i$ are the standard deviation and average of the three rate of smoothness measurements taken for each independent 100 m section.

In order to determine how each of the lightweight profilers would perform under similar conditions, discrete comparisons of reproducibility and repeatability were conducted on RS(0) and IRI data measured by each profiler on 420 simulated 300 m profile sections. These comparisons were then used to plot curves indicating the probability that each of the three lightweight profilers would meet MTO's current acceptance criteria. For these purposes, it was assumed that a lightweight profiler would be acceptable if it met both acceptance criteria at least 70 percent of the time.

5.2.1 Rate of Smoothness (RS) Measurements

The RS(0) data that was generated by each of the lightweight profilers was adjusted using equation (i) for the average differences that were recorded between all three lightweight profilers and all three California profilographs. This was done, in order to more fairly compare the two different types of devices. The revised RS(0)'s were then used to generate the reproducibility and repeatability probability curves.

Reproducibility:

Figure 12 shows the probability that the average RS(0) is likely to deviate from the overall mean established by all six profilers (by various percentages). Based on MTO's current acceptable deviation limit of 4 percent, it appeared that only Lightweight Profiler #2 would meet MTO's reproducibility requirement, at least 70 percent of the time. The curves also indicated that it is unlikely that Lightweight Profiler #3 would meet the reproducibility requirement for RS(0), based on the data that was submitted.

Additional analysis showed that if Lightweight #3 was dropped from the analysis and if the reproducibilities were recalculated based on the overall means established by the remaining 5 profilers, then the curve representing Lightweight Profiler #2 would shift to the right, representing a higher probability of reproducibility. If the acceptance limit was also allowed

to marginally increase to 4.5 percent then Lightweight Profiler #1 would also meet MTO's reproducibility requirement more than 70 percent of the time.

Repeatability:

Figure 13 shows the probability that the average coefficient of variation for the 3, 100 sections within any 300 m section of a single wheelpath would meet MTO's repeatability requirement. Based on an acceptance limit of 5 percent, the analysis showed that all three of the lightweight profilers would meet MTO's repeatability requirement at least about 70 percent of the time, with Lightweight #2 again performing the best of the three.

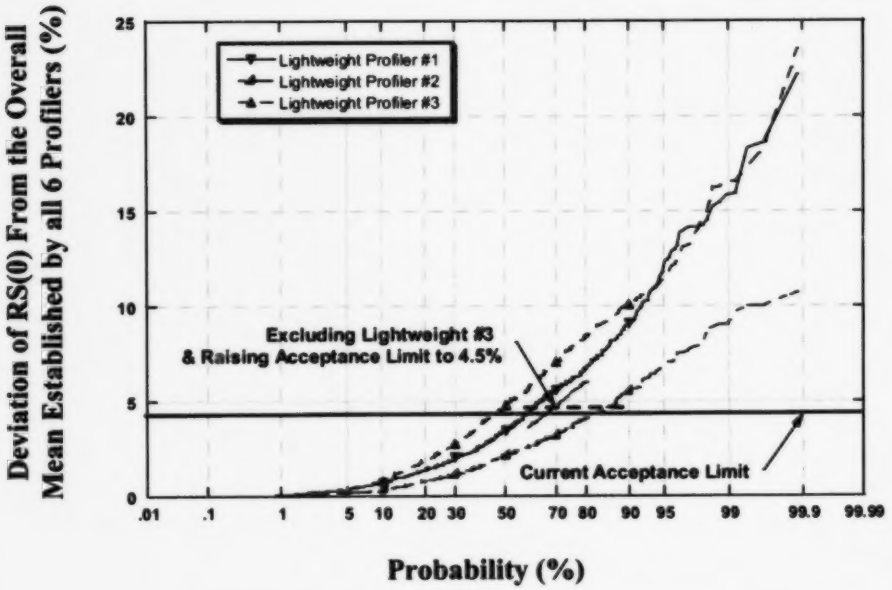


Figure 12 - Probability That Each Lightweight Profiler Would Meet MTO's Reproducibility Requirement for RS(0) (420, 300 m Sections)

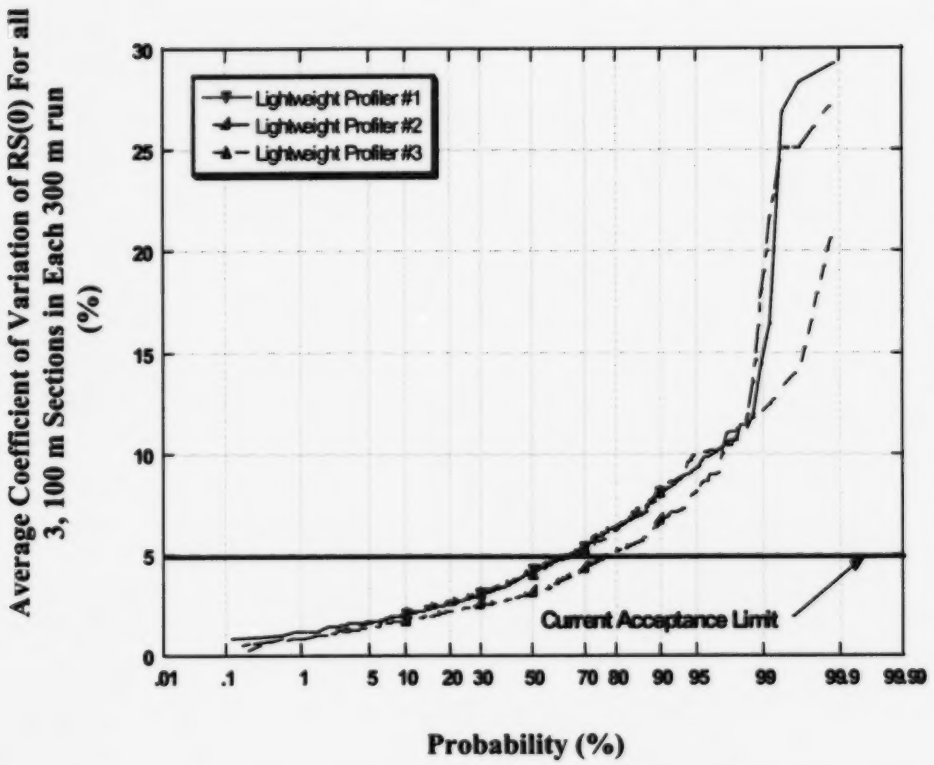


Figure 13 - Probability That Each Lightweight Profiler Would Meet MTO's Repeatability Requirement for RS(0) (420, 300 m Sections)

5.2.2 IRI Measurements

Simulated correlations were also conducted with the IRI measurements taken by the lightweight profilers. However, since the California Profilographs are not able to measure IRI, the lightweight profilers were only compared with each other (i.e. the average of all 3). It should be noted that, although the ARAN is also able to measure IRI, it was not included in the analysis because the comparison between the lightweight profilers and the California Profilographs alone was of more concern.

Reproducibility:

Figure 14 shows the probability that the average IRI for each lightweight profiler is likely to deviate from of the overall mean established by all three lightweights. If it is assumed that a

deviation limit of 4 percent would be considered acceptable [as MTO currently accepts for RS(0)], then it appears that all three Lightweight Profilers would meet MTO's reproducibility requirement more than 85 percent of the time.

Repeatability:

Figure 15 shows the probability that the average coefficient of variation for the 3, 100 sections within any 300 m section of a single wheelpath would meet MTO's repeatability requirement for IRI. If it is assumed that a limit of 5 percent would be considered acceptable (as MTO currently accepts for RS(0)), then it appears that all three of the lightweight profilers would meet MTO's repeatability requirement more than 90 percent of the time, with Lightweight #2 performing the best of the three.

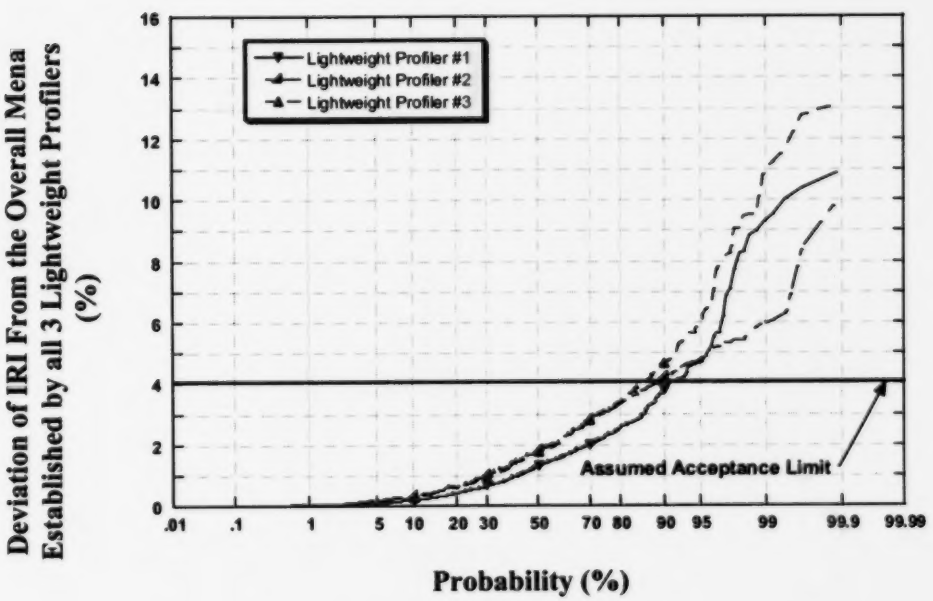


Figure 14 - Probability That Each Lightweight Profiler Would Meet MTO's Proposed Reproducibility Requirement for IRI (420, 300 m Sections)

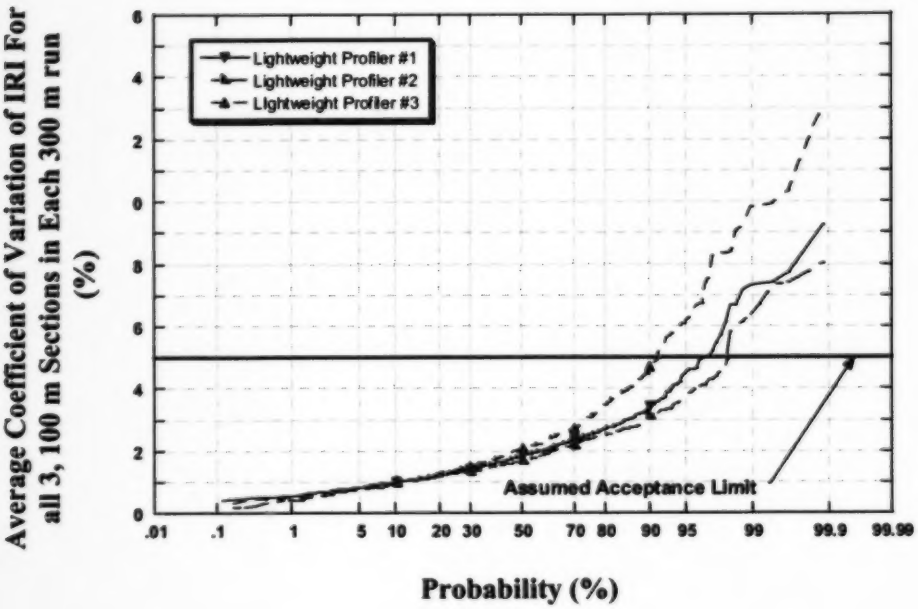


Figure 15 - Probability That Each Lightweight Profiler Would Meet MTO's Repeatability Requirement for IRI (420, 300 m Sections)

5.2.3 Development of IRI-Based Acceptance Limits

In Subsection 5.1.2, a linear correlation was developed between IRI measured by the lightweight profilers and PI measured by the California profilographs (Equation ii).

Based on this equation, and current PI based limits (see Section 5.0), the following "equivalent" IRI-based acceptance limits in m/km, (rounded to the nearest 0.05) were developed for asphalt pavements:

Maximum Bonus:	< 0.50
Bonus:	0.50 to <0.70
Full Pay:	0.70 to 1.10
Price Reduction:	>1.10 to 1.35
Rejectable:	>1.35

5.2.4 Scallops or "Must-Grinds" (A Comparison Between Lightweight Profilers and California Profilographs)

The issue that has the most financial impact for smoothness on contracts in Ontario is the number and the amplitudes of the individual bumps and dips which are collectively referred to as "scallops" (or the more commonly used term "must-grinds") that are recorded. Therefore, as part of this investigation, each lightweight profiler was required to produce a PI-based profile trace for each run and then determine the amplitudes of each of the scallops that were identified.

Table 5 shows the average number of scallops that were identified by each lightweight profiler in their three runs, in comparison to the average number that were identified by the three California Profilographs in their single runs for each of the 15 pavement sections that were tested. The scallops are broken down on the basis of the three different amplitude categories which Ontario currently uses to assess payment adjustments, i.e. 10-11.5mm, 12.0-14.5 mm and greater than 14.5 mm.

The results show that for the asphalt pavements only, Lightweight Profiler #1 best emulated the California Profilographs for the scallops that were up to 14.5 mm in amplitude but produced somewhat more scallops than the profilographs when their amplitudes were greater than that. Lightweight Profiler #3 best emulated the California Profilographs for the scallops with amplitudes greater than 14.5 mm but did poorly when comparing the bulk of the scallops that had amplitudes less than that. Although, on balance, it appears that Lightweight Profiler #2 best emulated the California Profilographs in terms of the combined total number of scallops that were recorded in all three categories, it produced somewhat less scallops than the profilographs in the 10 to 11.5 mm category and somewhat more for the ones with amplitudes greater than 14.5 mm.

Based on these results, it appears that really only one of the lightweight profilers can adequately simulate California Profilographs in the determination of scallops. However, even before this device could be used on an Ontario contract, both MTO and the Contractors would have to accept some differences in scallop detection.

Two of the manufacturers of the lightweight profilers also provided IRI-based "scallop" information using a simulation that was first formulated in a paper by *Fernando et al.* published [11]. Although the data is not being presented here, spot comparisons showed that, in general, the heights and numbers of IRI-based scallops that were reported from the lightweight profilers are significantly greater than those indicated on the traces produced by the profilographs.

Table 3 - Comparison of the Average Number of Scallops that Each Individual Lightweight Profiler Recorded for the three amplitude ranges versus the Number Recorded by the Three Profilographs

Pavement Section	Lightweight Profiler #1			Lightweight Profiler #2			Lightweight Profiler #3			Amplitude Range For Average of all 3 Profilographs		
	10-11.5	12.0-14.5	>14.5	10-11.5	12.0-14.5	>14.5	10-11.5	12.0-14.5	>14.5	10-11.5	12.0-14.5	>14.5
1A	0	0	0	0	0	0	0	0	0	0	0	0
1B	1.3	0	2	2.7	0.7	1	0	1	1	1	2	1
2	5.7	5	1.7	2.7	4	1.3	3.3	2.7	0	5.3	2	1
3A	5.7	1.3	0	3	3.3	0	0	2	0	4.7	3	0
3B	3	2.3	1.7	2.3	1.7	1	0	2	1.3	3.3	3	0
4A	7.7	1.7	0.3	4	1.3	0	0	1.3	0	5.3	1	0
4B	6.7	1.7	3	4	1	2	2	1	2	7.7	1	2
5A	18	3.7	4.3	9	3.7	4	2	2.7	4	12.3	6	2
5B	47.3	27	10	26.7	20.3	5	5.7	13	3.7	25.7	24.8	7
6A	10.7	12.7	8.7	10	9.7	8	4.3	8	5.3	13.3	13	4.7
6B	7	2	0.3	7.7	2	0	2.3	1.7	0.3	5.3	2.7	0
7A	0	0	0	0	0	0	0	0	0	0	0	0
7B	0	1	0	2.7	2	0	0	1	0	1.7	2	0
8A	2	2.7	3.3	2.7	0	0	0.7	0.7	0.3	1.7	0	0
8B	11.3	10.7	5	4.7	9.7	3	2.7	6	2	10.8	7	3
Totals For All Pavements	126.4	71.8	40.3	82.2	59.4	25.3	23	43.1	19.9	98.1	67.5	20.7
	238.5			166.9			86.0			186.3		
Totals For Concrete Pavements Only	77.9	41.4	21.3	43.1	34.4	13.0	10.4	22.7	10.7	49.8	39.8	13.0
	140.6			90.5			43.8			102.6		
Totals For Asphalt Pavements Only	48.5	30.4	19	39.1	25	12.3	12.6	20.4	9.2	48.3	27.7	7.7
	97.9			76.4			42.2			83.7		

*Note: The numbers are based on the number of times that a Lightweight profiler recorded each scallop in its three runs (e.g. 1=3 of 3 runs or 0.66=2 of 3 runs). For the profilographs, the number of scallops is based on the number of times that each scallop was recorded by the three profilographs combined. However, for the concrete sections, the number is based on 3 profilographs running twice.

6. SUMMARY OF RESULTS AND FINDINGS

Ten asphaltic (212 - 100 m sublots) and 5 Portand cement (72 - 100 m sublots) concrete pavement sections were measured 3 times by 3 different lightweight profilers, 3 times by MTO's ARAN and once by three different California Profilographs (twice for the concrete sections). These measurements have lead to the following results:

1) Correlations Between Average PI's and IRI's Measured Using Lightweight Profilers, California Profilographs and MTO's ARAN:

- Excellent linear relationships (correlation coefficients ≥ 0.99) were found between the PI's measured by the lightweight profilers versus the PI's measured by the California profilographs for the asphalt pavement sections which were measured using a 0 blanking band or for the concrete sections which were measured using either a 0 or a 5 mm blanking band.
- Excellent linear relationships (correlation coefficients ≥ 0.99) were found between the IRI's measured by the lightweight profilers and the IRI's measured by MTO's ARAN for both the asphalt and the concrete pavement sections that were tested.
- Very good linear relationships (correlation coefficients between 0.93 and 0.97) were found between the IRI's measured by the lightweight profilers versus the PI's measured by the California Profilographs for the asphalt pavement sections when the PI's were measured using a 0 blanking band or for the concrete sections when the PI's were being measured using either a 0 or a 5 mm blanking band.

2) Reproducibilty/Repeatabilty of PI and IRI Measured By Lightweight Profilers:

- All three of the lightweight profilers exhibited excellent reproducibility and repeatability when measuring IRI.
- All three lightweight profilers exhibited good repeatability when measuring rate of smoothness (or RS).
- Only one of the three lightweight profilers (Lightweight Profiler #2) exhibited acceptable (i.e. very good) reproducibility when measuring rate of smoothness (or RS).

3) Determination of equivalent IRI-based Acceptance Limits:

Using the correlation equations that were developed between the IRI measurements taken by the lightweight profilers and the PI measurements taken by the California Profilographs in this study, the following equivalent IRI-based acceptance limits were determined from the PI-based ones that are currently being used for asphaltic concrete pavements:

Table 4 - "Equivalent" IRI-based Acceptance Limits

Asphaltic Concrete Surface Courses Pay Categories Using a 0 Blanking Band	Current PI-Based Acceptance Limits mm/km	Equivalent IRI-Based Acceptance Limits m/km
Maximum Bonus	< 150	<0.50
Bonus	150 to <230	0.50 to < 0.70-
Full Payment	230 to 430	0.70 to 1.10
Price Reduction	>430 to 550	> 1.10 to 1.35
Rejectable	> 550	> 1.35

4) Comparison of Scallops Measured By California Profilographs and Lightweight Profilers:

- Lightweight Profiler #1 was able to simulate the locations and heights of the scallops with amplitudes less than 14.5 mm that were measured by the Profilographs very well. However, it was not very good in simulating scallops with heights larger than that.
- Lightweight Profiler #3 was able to simulate the locations and heights of scallops with amplitudes more than 14.5 mm that were measured by the profilographs very well. However, it appeared to be very poor in simulating scallops with amplitudes less than that.
- Although overall, lightweight Profiler #2 seemed best able to simulate the heights and locations of the scallops at least 12.0 mm in amplitude, it produced somewhat less scallops than the profilographs, for those less than 12.0 mm.
- At the time of writing of this report, none of the Lightweight Profilers were able to demonstrate IRI-based "scallops" which resembled those produced by the California Profilographs.

5) Additional Findings and Observations:

In order to consider lightweight profilers for smoothness acceptance on MTO contracts, the following additional findings that were made during the fieldwork must be considered:

- Lightweight profilers can only be operated when the pavement is completely dry.
- Lightweight profilers seem to be somewhat more sensitive to debris on the road (i.e. the sensors measure and include them as part of the roughness calculation) than the profilographs (i.e. the measuring wheel for a profilograph would simply depress small debris and produce a spike that's not counted).
- The beams from the sensors will penetrate pavement cracks and joints whereas a profilograph measuring wheel will simply bridge over it.
- It appeared that one of the sensors that was being used by one of the lightweight profilers may have been affected by colder temperatures.

- There is currently no IRI-based "scallop" (although this is presently being worked on).
- None of the lightweight profilers were able to demonstrate a good method of maintaining a proper offset, nor could they produce a continuous profile trace which MTO currently requires for contract administration purposes.

7. CONCLUSIONS

Based on the original objectives of the this investigation, the following conclusions can be drawn:

1) For lightweight profilers to replace California Profilographs in Ontario for measuring RS (or PI):

- Current acceptance limits for reproducibility and repeatability (in %) which are being used during MTO's yearly correlations would have to change slightly (i.e. only one lightweight profiler was found to meet both current requirements);
- Changes would be needed, in order to accommodate differences in the way that individual bumps (or "scallops") are measured for acceptance; and
- Some hardware and/or software changes would be needed to meet MTO's current administrative requirements (i.e. maintaining a proper offset and producing a continuous profile trace).

2) For IRI-based smoothness acceptance of new construction in Ontario:

- California profilographs would have to be replaced by inertial profilers;
- New IRI-based acceptance limits (given in Table 4), would have to replace the current PI-based ones;
- The yearly correlations would have to be based on IRI [although the % acceptance limits for reproducibilty and repeatability can remain the same as they are now]; and
- New IRI-based acceptance criteria would have to be developed for individual bumps. However, as an interim procedure, "Scallops" could be identified from PI-based profile traces (although changes would be needed, in order to accommodate the differences in the way "scallops" are measured).

3) For IRI measurements taken on new construction to form the basis for future (i.e. network level) monitoring of the same pavements:

- Equation ii (given in Section 5.1.3) would have to be used to convert IRI measurements taken by the Lightweight profilers to equivalent measurements taken by the ARAN.

8. FUTURE WORK

The Ministry will continue to move forward in its investigation of lightweight profilers for IRI-based smoothness acceptance on Ministry contracts by:

1) Conducting, side-by-side IRI measurements taken by Lightweight or other inertial Profilers with PI measurements taken by California Profilographs on several trial contracts to further validate the IRI-based acceptance limits that have been determined during this investigation and to compare PI and IRI-based price-adjustments in real contract situations.
2) Investigating the use of software such as @ProVal 2.0, which has the capability of calculating IRI-based scallops from the data files provided by the lightweight and other inertial profilers.

These further steps will allow MTO to continue its movement towards IRI-based acceptance for newly-constructed pavements and to integrate this information into the data base used for network level monitoring in Ontario.

9. ACKNOWLEDGEMENTS

The Authors wish to express their thanks to MTO's Concrete Section (particularly Hannah Schell and Chris Wojcik) and the Pavements and Foundations Section (particularly Tom Kazmierowski and Roy Clark); for their assistance in providing and operating MTO's California Profilograph and ARAN, respectively and Eastern Region's Dave McNeely and John Isaac as well as Central Region's Dave Carter, John Dybszak and Ho-Lik Iu for their assistance in selecting field locations, arranging traffic control and conducting the fieldwork.

APPENDIX 1

Some Ontario-Specific Mix Designations:

HL1: A dense-graded surface course mix consisting of premium quality, crushed, coarse aggregates with a maximum aggregate size of 16 mm. It is normally used on roads with volumes between 2500 and 5000 AADT per lane.

HL3: A dense-graded surface course mix with similar gradation to HL1 but with lower quality requirements for the aggregates.

HL4: A surface or binder course mix with a maximum aggregate size of 19.0 mm. It is primarily used on two-lane highways in Northern Ontario or as a binder course in Southern Ontario where HL8 is not available.

RHM: Hot mix usually containing up to 35 percent recycled mix having the same gradation and uses as either HL4 or HL8. In this report, RHM refers exclusively to the HL4 surface course gradation.

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10. Ministry of Transportation, Ontario (MTO), Special Provision SP103 F34, "Asphaltic Concrete Surface Tolerance and Payment Adjustment for Surface Smoothness", 2004

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Glossary

Blanking band - means a band of uniform height "B" in mm and with a length equal to 100 m, which is positioned optimally between the highs and the lows of the profile trace to "blank out" as much of the profile trace as possible.

International Roughness Index (IRI) - is a specific mathematical transform of a true profile in which a low pass filter (usually consisting of a moving average with a 250 mm base length) followed by a "Quarter Car Filter" are applied to the true profile then the filtered result is accumulated by summing the absolute values, dividing by the profile length and multiplying by 1000.

Profile index - means the rate of smoothness averaged over both wheel paths for a 100 m pavement section.

Quality Assurance (QA) - Measurements or other activities performed by the Owner or the Owner's representative to monitor quality.

Quality Control (QC) - Measurements or other activities performed by the Contractor to monitor quality.

Quarter Car Filter - calculates the suspension deflection of a simulated mechanical system with a response similar to one corner (a quarter) of a passenger car travelling at 80 km/hr.

Rate of smoothness (RS) - means the amplitudes of all of the individual bumps and depressions outside of a blanking band which are greater than 0.8 mm and which also extend at least 0.6 m as measured by a PMD along the profile length; are all added together and then divided by the sublot length; expressed in mm/km.

Scallop - means a bump or depression in the pavement surface at a location which is automatically determined by the PMD's computer as either a line through the profile trace for McCracken profilographs or a shaded mark above the trace for Cox profilographs, which is at least "S" mm ("S"=10 mm shall be the upper limit for acceptability of asphaltic concrete) above or below a 7.5 m long baseline which is constantly changing in elevation due to the surrounding pavement.

Sublot - means a continuous traffic lane of pavement; excluding the shoulder, normally having a length of 100 m, measured horizontally in the direction of travel for highway

survey purposes.

Wheel paths - means 1.0 m on each side of the centreline of the actual trafficked lane. The trafficked lane does not include adjacent paved areas such as paved shoulders or tapers.